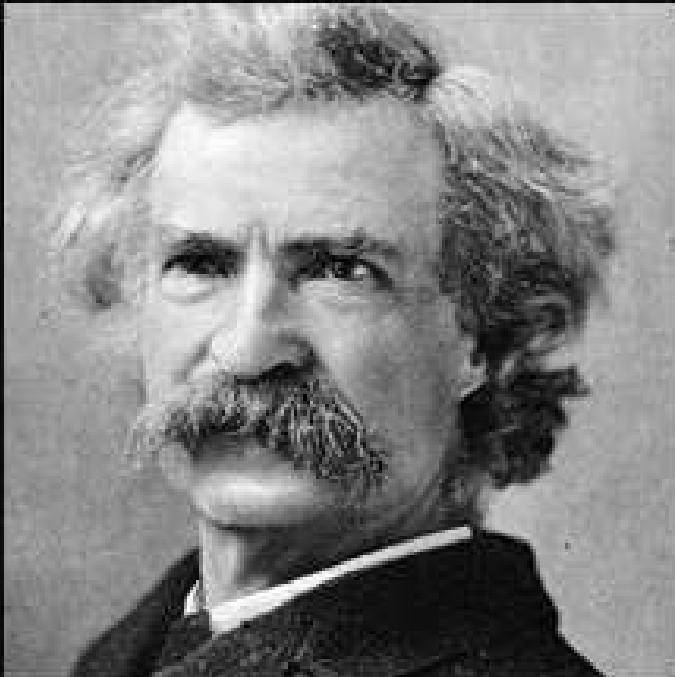


Some original SUSY literature:



The reports of my death have
been greatly exaggerated.

~ Mark Twain

New SUSY Higgs Benchmarks for the LHC – HL-LHC and ILC implications

Sven Heinemeyer, IFT/IFCA (CSIC, Madrid/Santander)

Corpus Cristi, 05/2019

- Motivation
- New MSSM Higgs Benchmarks for the LHC
- Implications for the HL-LHC and the ILC
- Conclusions

1. Motivation

Two facts:

We have a discovery!

The SM cannot be the ultimate theory!

Conclusion: It cannot be “the SM Higgs” !

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We have a discovery!

The SM cannot be the ultimate theory!

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Q: Does the BSM physics have any (relevant) impact on the Higgs?

Q': Which model?

1. Motivation

Two facts:

We have a discovery!

The SM cannot be the ultimate theory!

Conclusion: It cannot be “the SM Higgs”!

Q: Does the BSM physics have any (relevant) impact on the Higgs?

Q': Which model?

A1: check changed properties

A2: check for additional Higgs bosons

A2': check for additional Higgs bosons above and below 125 GeV

Models with extended Higgs sectors:

1. SM with additional Higgs singlet
 2. Two Higgs Doublet Model (THDM): type I, II, III, IV
 3. Minimal Supersymmetric Standard Model (MSSM)
 4. MSSM with one extra singlet (NMSSM)
 5. MSSM with more extra singlets
 6. SM/MSSM with Higgs triplets
 7. ...
- ⇒ BSM models without extended Higgs sectors still have changed Higgs properties (quantum corrections!)
- ⇒ SM + vector-like fermions, Higgs portal, Higgs-radion mixing, ...

Which model should we focus on?

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Some “recent” measurements:

- top quark mass
- Higgs boson mass
- Higgs boson “couplings”
- Dark Matter (properties)

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Which model should we focus on? \Rightarrow experimental data as guidance!

Some “recent” measurements:

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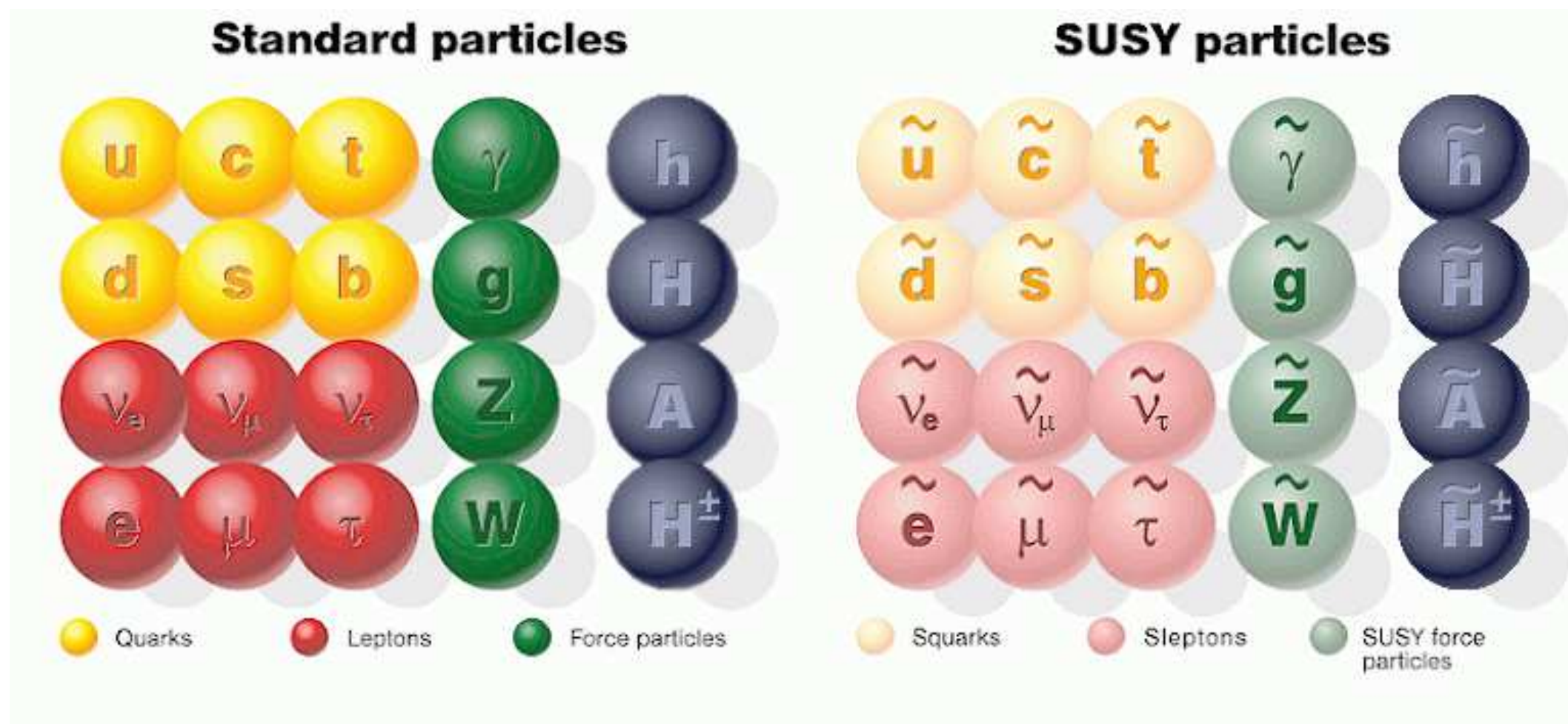
Simple SUSY models predicted correctly:

- top quark mass
- Higgs boson mass
- Higgs boson “couplings”
- Dark Matter (properties)

\Rightarrow good motivation to look at SUSY! :-)

The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles



Problem in the MSSM: more than 100 free parameters

Nobody(?) believes that a model describing nature has so many free parameters!

A. Unconstrained models (MSSM):

agnostic about how SUSY breaking is achieved

no particular SUSY breaking mechanism assumed, parameterization of possible soft SUSY-breaking terms

most general case: 105 new parameters: masses, mixing angles, phases
(\Rightarrow many (close to) zero according to experimental data)

\Rightarrow no model missed (within the MSSM)

$\Rightarrow \mathcal{O}(100)$ parameters difficult to handle

B. Constrained models:

CMSSM, NUHM1, NUHM2, SU(5), mAMSB, sub-GUT, FUTs, ...:

assumption on the scenario that achieves spontaneous SUSY breaking

\Rightarrow prediction for soft SUSY-breaking terms
in terms of small set of parameters

\Rightarrow easy to handle, but not all relevant phenomenology captured

C. Benchmark scenarios:

fix all-2 MSSM parameters in a smart way, explore benchmark planes

\Rightarrow easy to handle, interesting phenomenology captured!

The MSSM Higgs sector:

Enlarged Higgs sector: Two Higgs doublets

$$H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix}$$
$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix}$$

$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.})$$
$$+ \underbrace{\frac{g'^2 + g^2}{8}}_{\text{gauge couplings, in contrast to SM}} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}}_{\text{SM}} |H_1 \bar{H}_2|^2$$

physical states: h^0, H^0, A^0, H^\pm Goldstone bosons: G^0, G^\pm

Input parameters: (to be determined experimentally)

$$\tan \beta = \frac{v_2}{v_1}, \quad M_A^2 = -m_{12}^2 (\tan \beta + \cot \beta)$$

The MSSM Higgs sector: with \mathcal{CP} violation

Enlarged Higgs sector: Two Higgs doublets

$$H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix}$$
$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix} e^{i\xi}$$

$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.})$$
$$+ \underbrace{\frac{g'^2 + g^2}{8}}_{\text{gauge couplings, in contrast to SM}} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}}_{\text{gauge couplings, in contrast to SM}} |H_1 \bar{H}_2|^2$$

physical states: h^0, H^0, A^0, H^\pm Goldstone bosons: G^0, G^\pm

Input parameters: (to be determined experimentally)

$$\tan \beta = \frac{v_2}{v_1}, \quad M_{H^\pm}^2$$

2 \mathcal{CP} -violating phases: $\xi, \arg(m_{12}) \Rightarrow$ can be set/rotated to zero

The Higgs sector of the cMSSM at the loop-level:

Complex parameters enter via loop corrections:

- μ : Higgsino mass parameter
- $A_{t,b,\tau}$: trilinear couplings $\Rightarrow X_{t,b,\tau} = A_{t,b,\tau} - \mu^* \{\cot \beta, \tan \beta\}$ complex
- $M_{1,2}$: gaugino mass parameter (one phase can be eliminated)
- M_3 : gluino mass parameter

\Rightarrow can induce \mathcal{CP} -violating effects

Result:

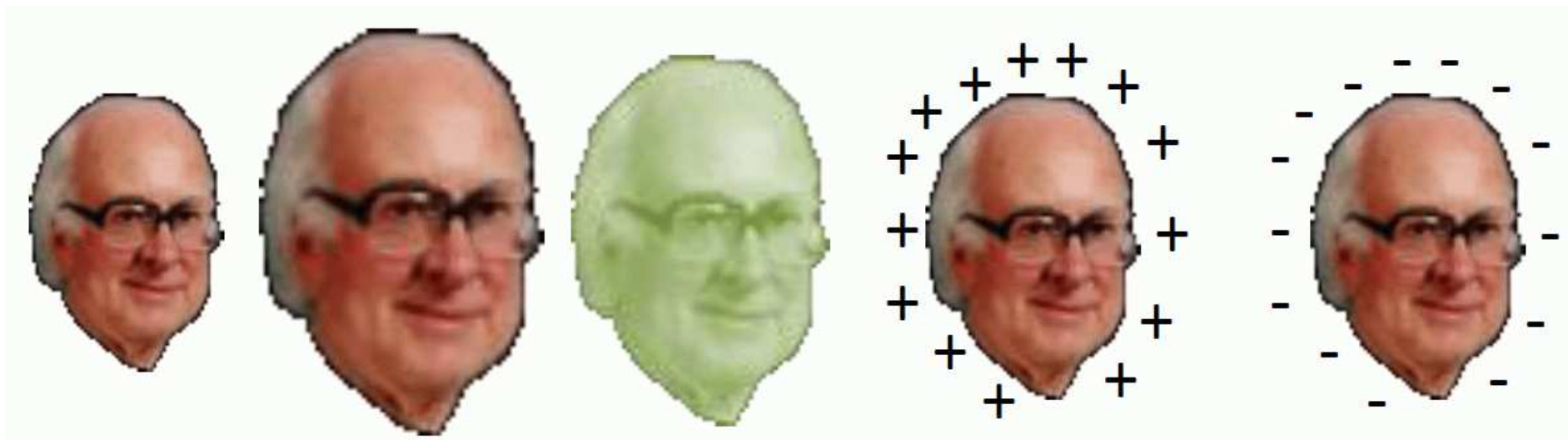
$$(A, H, h) \rightarrow (h_3, h_2, h_1)$$

with

$$m_{h_3} > m_{h_2} > m_{h_1}$$

\Rightarrow strong changes in Higgs couplings to SM gauge bosons and fermions

2. New MSSM Higgs Benchmarks for the LHC



Search for the MSSM Higgs bosons:

Smart choice of MSSM parameters?

→ investigate benchmark scenarios:

- Vary only M_A (or M_{H^\pm}) and $\tan \beta$
- Keep all other SUSY parameters fixed

[E. Bagnaschi, H. Bahl, E. Fuchs, T. Hahn, S.H., S. Liebler, S. Patel,
P. Slavich, T. Stefaniak, C. Wagner, G. Weiglein '18]

1. M_h^{125} scenario: 2HDM-like model
2. $M_h^{125}(\tilde{\tau})$ scenario: light staus: $h \rightarrow \gamma\gamma$, $H/A \rightarrow \tilde{\tau}\tilde{\tau}$
3. $M_h^{125}(\tilde{\chi})$ scenario: light EW-inos: $H/A \rightarrow \tilde{\chi}_i^0 \tilde{\chi}_j^0, \tilde{\chi}_k^\pm \tilde{\chi}_l^\mp$
4. M_h^{125} (alignment) scenario: h SM-like for very low M_A
5. M_H^{125} scenario: $M_H \sim 125$ GeV, all Higgses light
6. $M_{h_1}^{125}$ (CPV) scenario: complex phases, h_2 - h_3 interference

Not covered:

Set of benchmarks for low $\tan\beta$

[*H. Bahl, S. Liebler, T. Stefaniak '19*]

- use 2HDM as low-energy model
- (mainly) EFT calculation, RGE running to M_{SUSY}
- implemented in FeynHiggs (so far priv.)

Heavy SUSY particles: $M_{h,\text{EFT}}^{125}$

light EW-inos: $M_{h,\text{EFT}}^{125}(\tilde{\chi})$

Data to be taken into account:

- Higgs boson mass (LHC) \Rightarrow FeynHiggs

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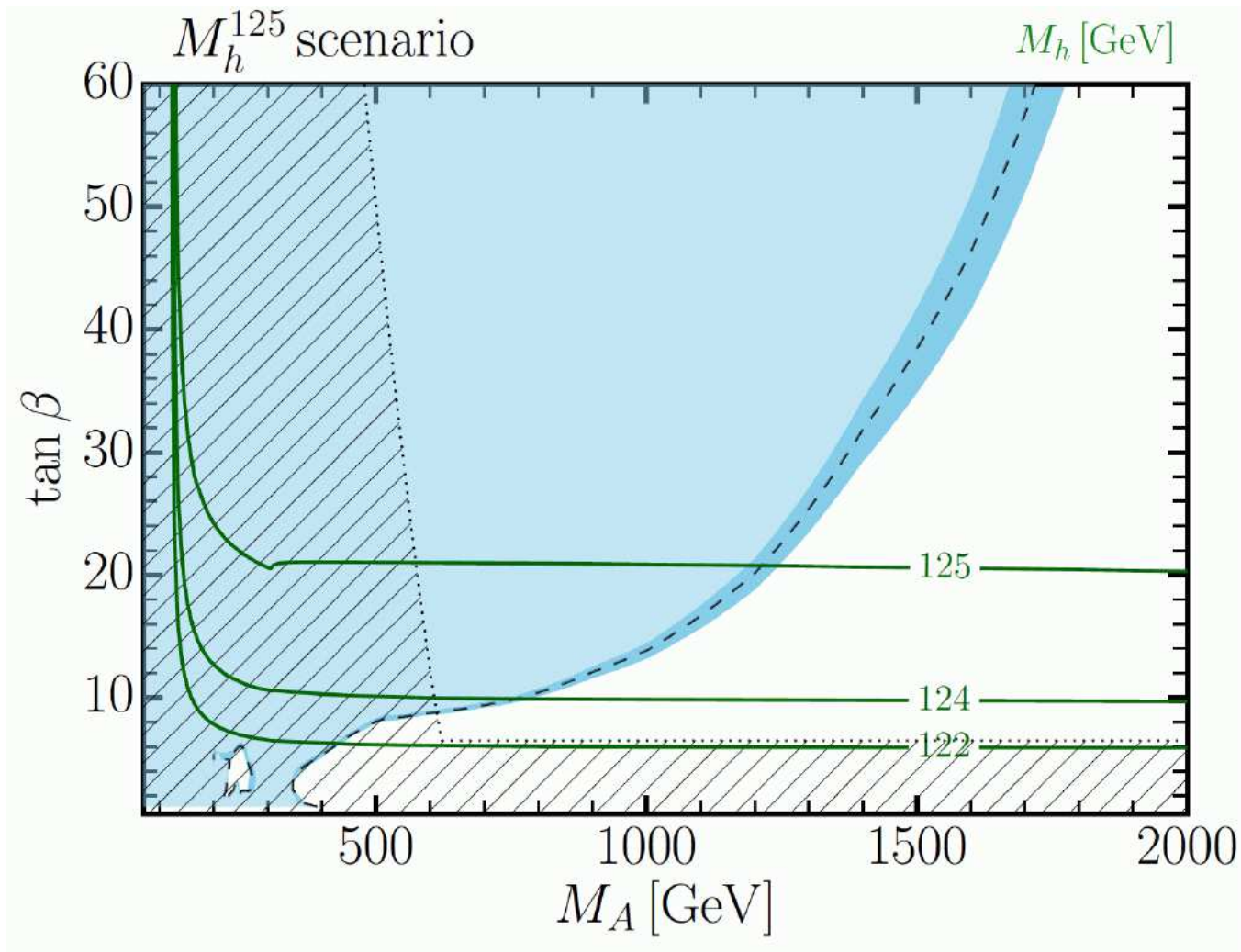
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- Higgs boson exclusion bounds (LHC, Tevatron, LEP) \Rightarrow HiggsBounds
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Data on purpose not to be taken into account:

- electroweak precision data
- flavor data
- astrophysical data (DM properties)



$$M_{\tilde{Q}_3} = M_{\tilde{U}_3} = M_{\tilde{D}_3} = 1.5 \text{ TeV}$$

$$M_{\tilde{L}_3} = M_{\tilde{E}_3} = 2 \text{ TeV}$$

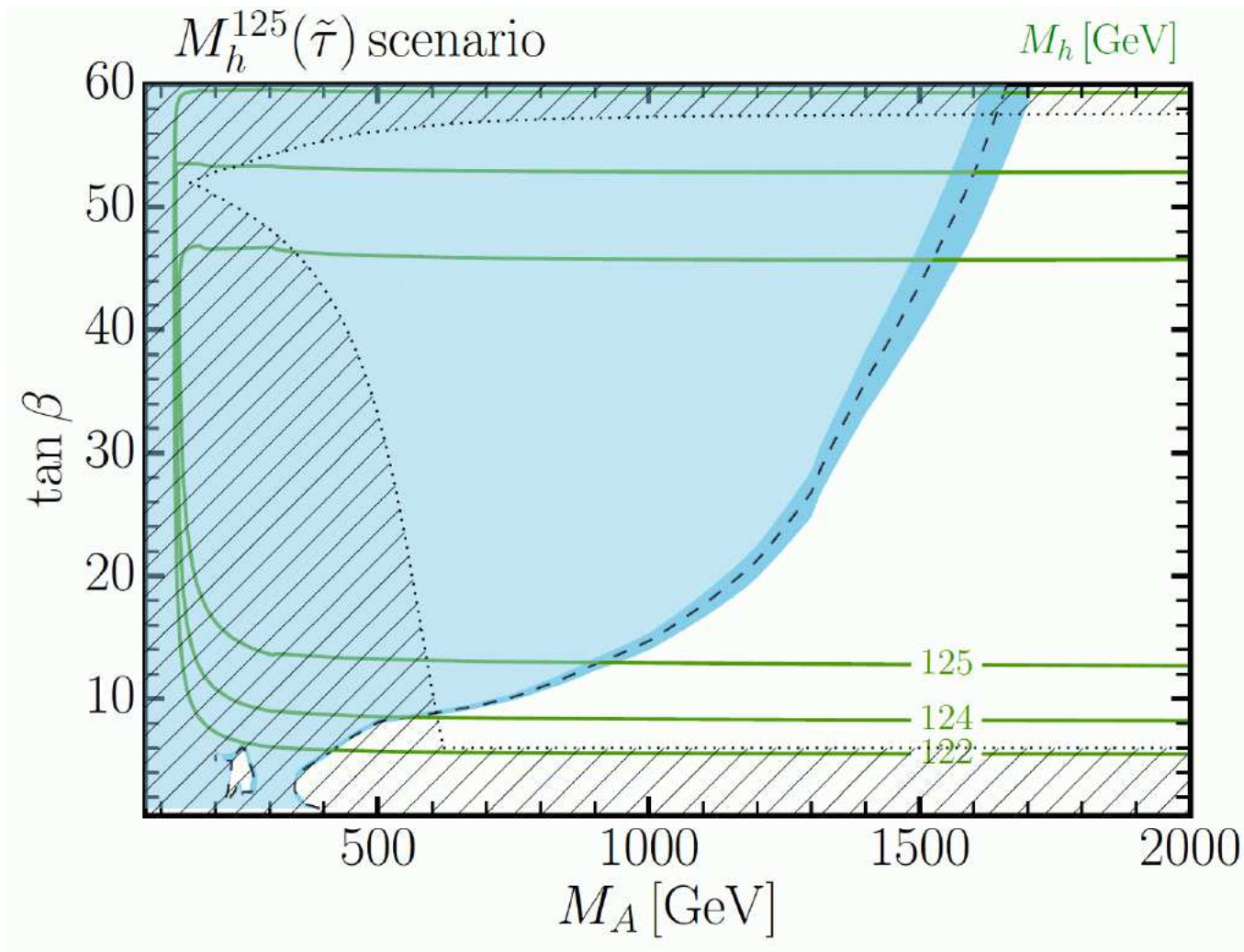
$$\mu = 1 \text{ TeV}, M_1 = 1 \text{ TeV}$$

$$M_2 = 1 \text{ TeV}, M_3 = 2.5 \text{ TeV}$$

$$X_t = 2.8 \text{ TeV}$$

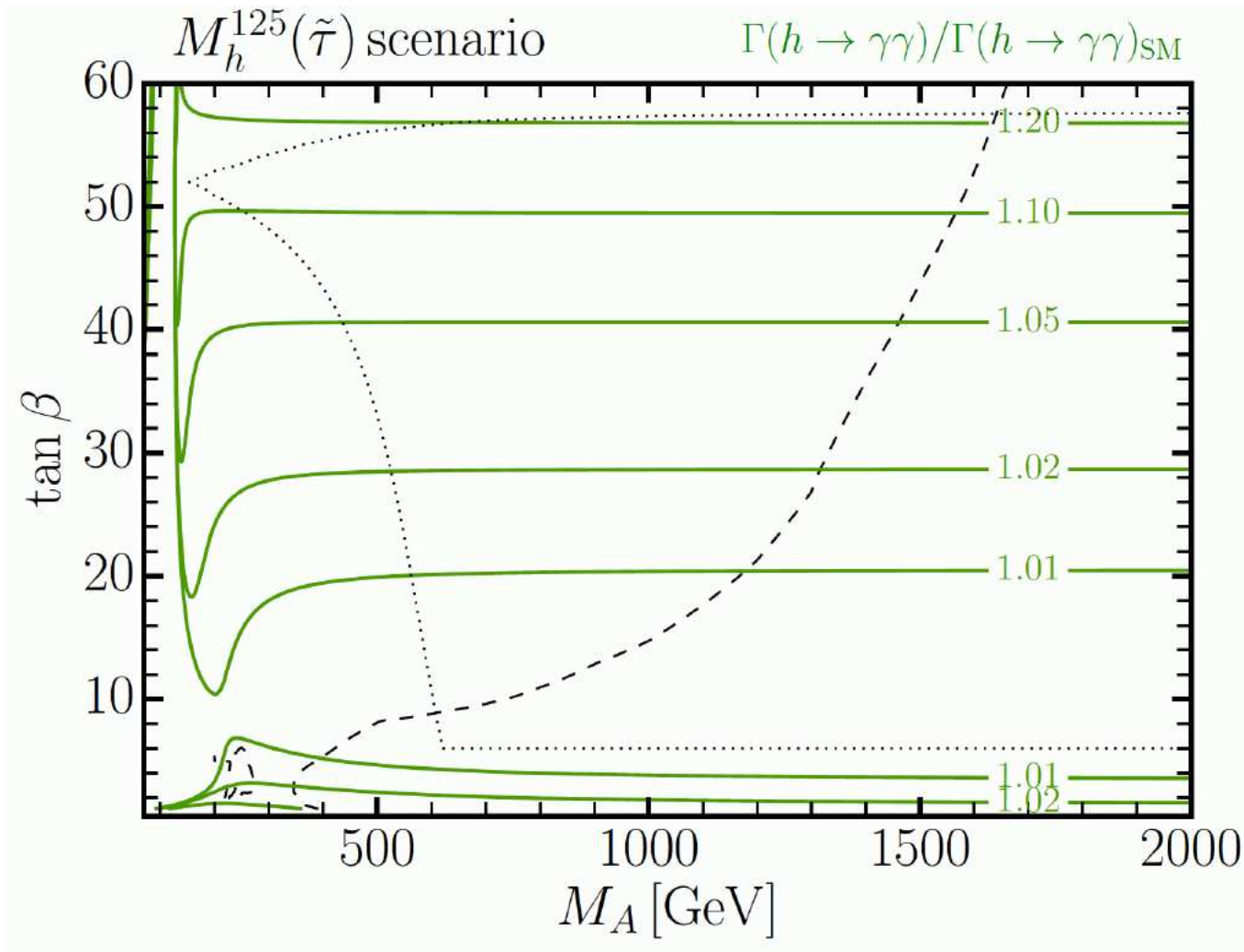
$$A_t = A_b = A_\tau$$

⇒ new vanilla benchmark model



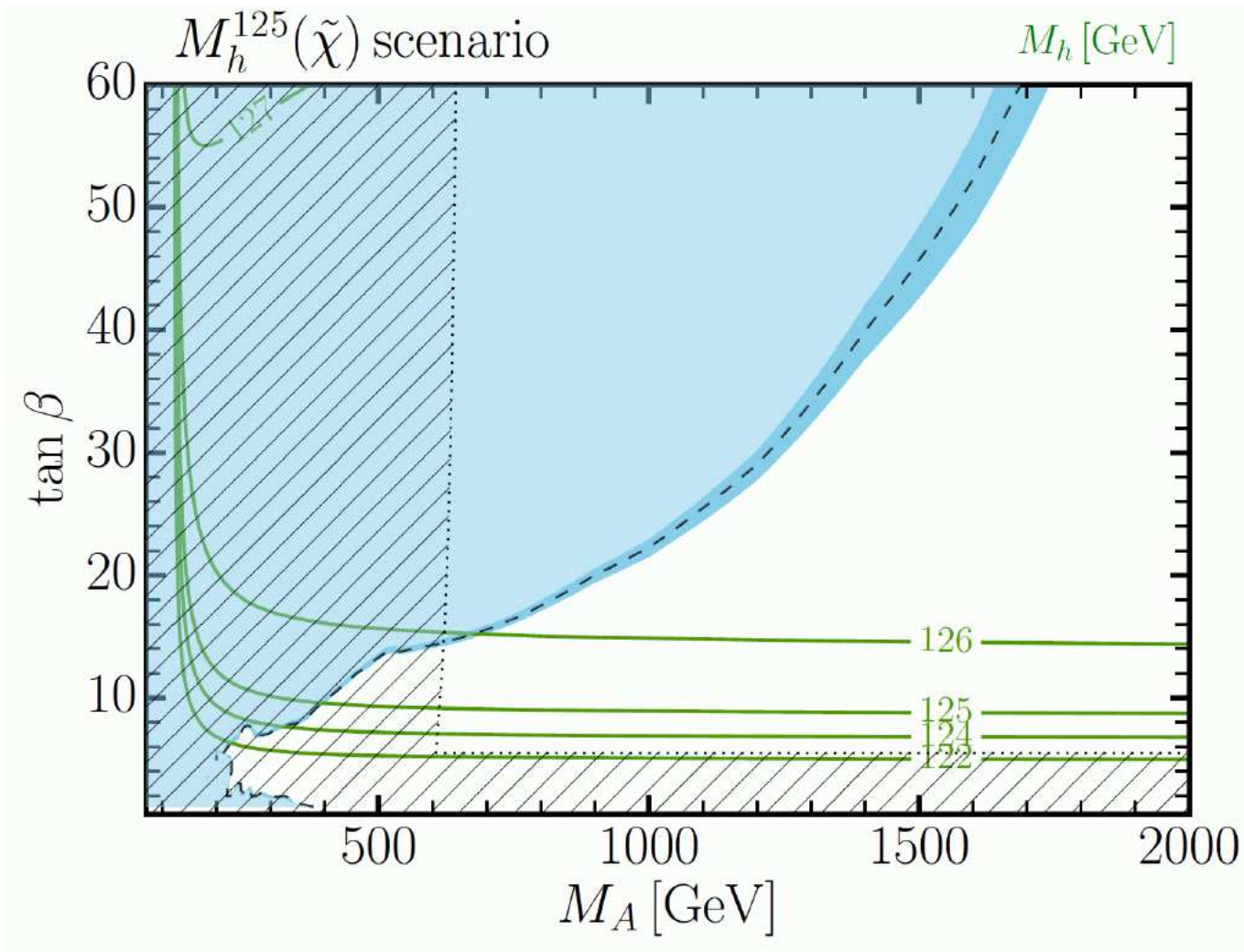
$$\begin{aligned}
 M_{\tilde{Q}_3} &= M_{\tilde{U}_3} = M_{\tilde{D}_3} = 1.5 \text{ TeV} \\
 M_{\tilde{L}_3} &= M_{\tilde{E}_3} = 350 \text{ GeV} \\
 \mu &= 1 \text{ TeV}, \quad M_1 = 180 \text{ GeV} \\
 M_2 &= 300 \text{ GeV}, \quad M_3 = 2.5 \text{ TeV} \\
 X_t &= 2.8 \text{ TeV} \\
 A_t &= A_b, A_\tau = 800 \text{ GeV}
 \end{aligned}$$

⇒ slightly reduced heavy Higgs coverage



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 M_{\tilde{Q}_3} &= M_{\tilde{U}_3} = M_{\tilde{D}_3} = 1.5 \text{ TeV} \\
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 A_t &= A_b, A_\tau = 800 \text{ GeV}
 \end{aligned}$$

⇒ strong impact on $\Gamma(h \rightarrow \gamma\gamma)$



$$M_{\tilde{Q}_3} = M_{\tilde{U}_3} = M_{\tilde{D}_3} = 1.5 \text{ TeV}$$

$$M_{\tilde{L}_3} = M_{\tilde{E}_3} = 2 \text{ TeV}$$

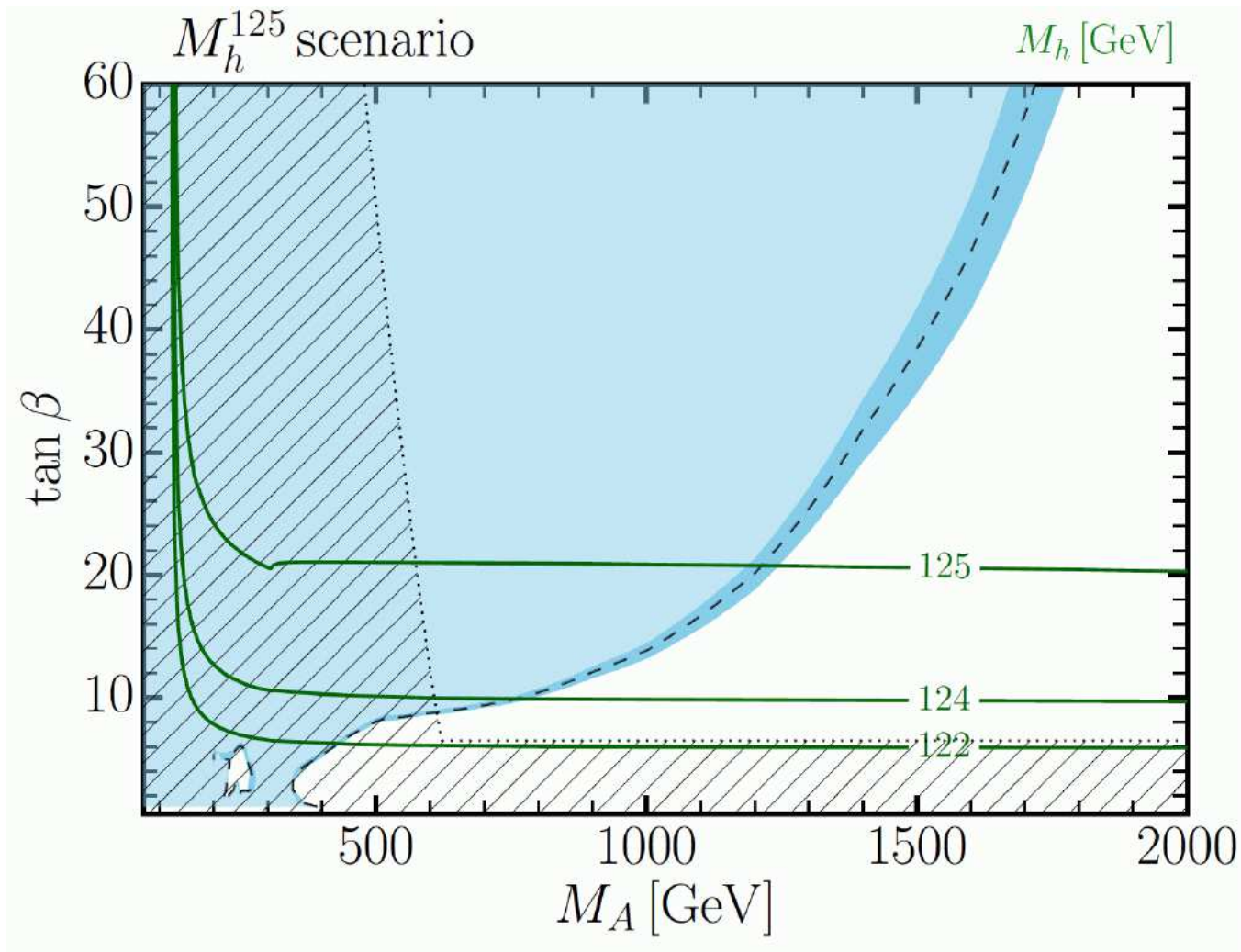
$$\mu = 180 \text{ GeV}, M_1 = 160 \text{ GeV}$$

$$M_2 = 180 \text{ GeV}, M_3 = 2.5 \text{ TeV}$$

$$X_t = 2.5 \text{ TeV}$$

$$A_t = A_b = A_\tau$$

⇒ strongly reduced heavy Higgs coverage



$$M_{\tilde{Q}_3} = M_{\tilde{U}_3} = M_{\tilde{D}_3} = 1.5 \text{ TeV}$$

$$M_{\tilde{L}_3} = M_{\tilde{E}_3} = 2 \text{ TeV}$$

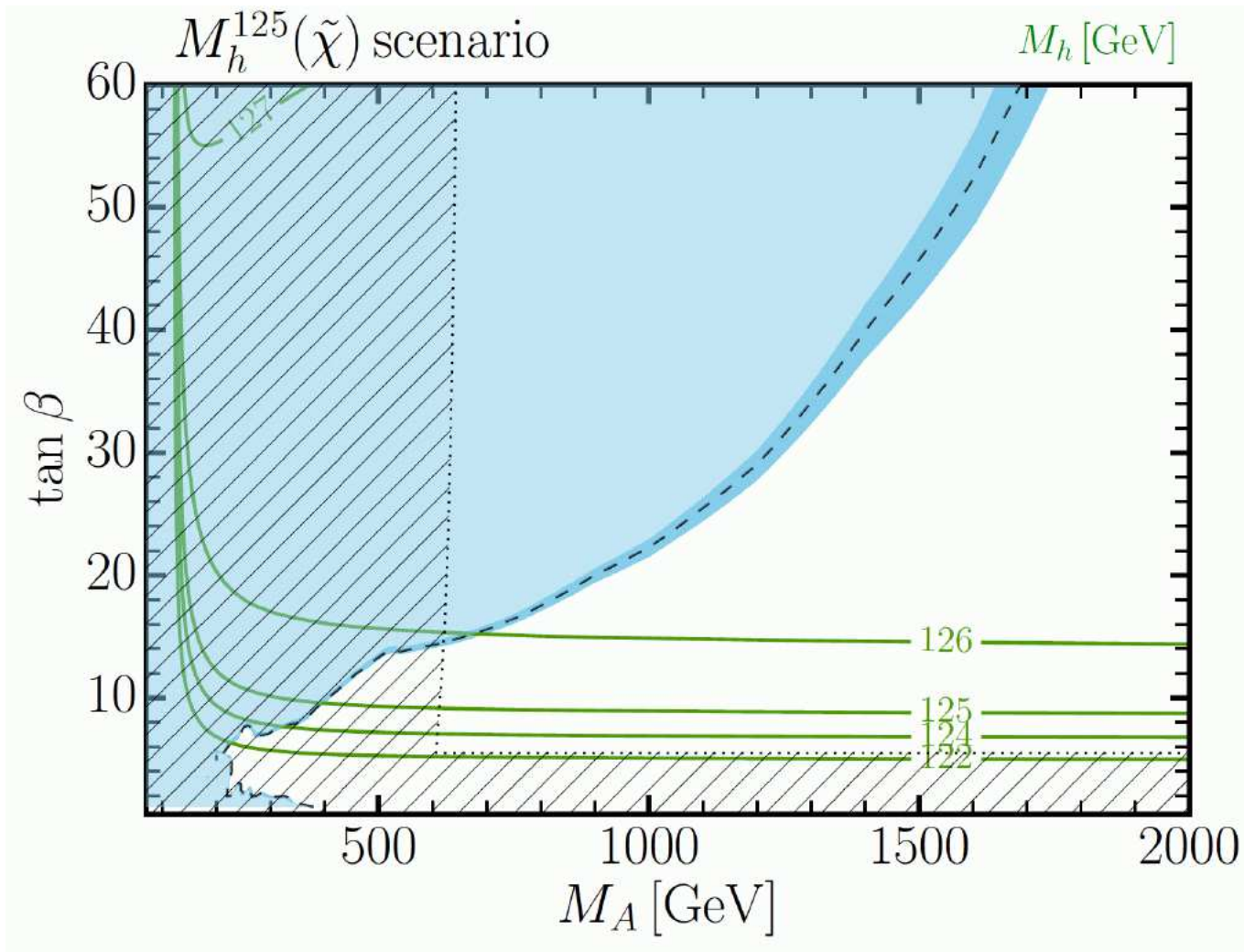
$$\mu = 1 \text{ TeV}, M_1 = 1 \text{ TeV}$$

$$M_2 = 1 \text{ TeV}, M_3 = 2.5 \text{ TeV}$$

$$X_t = 2.8 \text{ TeV}$$

$$A_t = A_b = A_\tau$$

⇒ new vanilla benchmark model



$$M_{\tilde{Q}_3} = M_{\tilde{U}_3} = M_{\tilde{D}_3} = 1.5 \text{ TeV}$$

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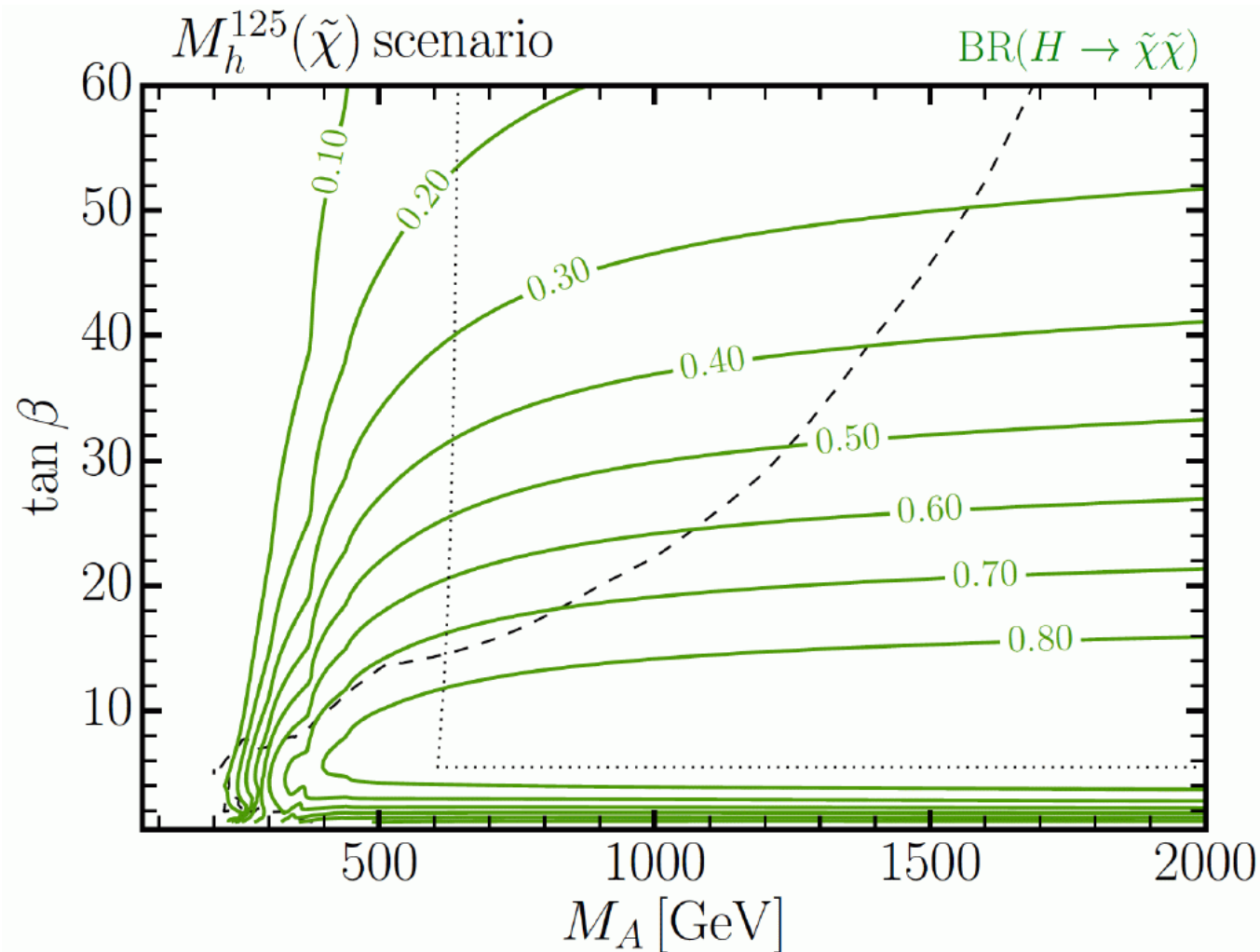
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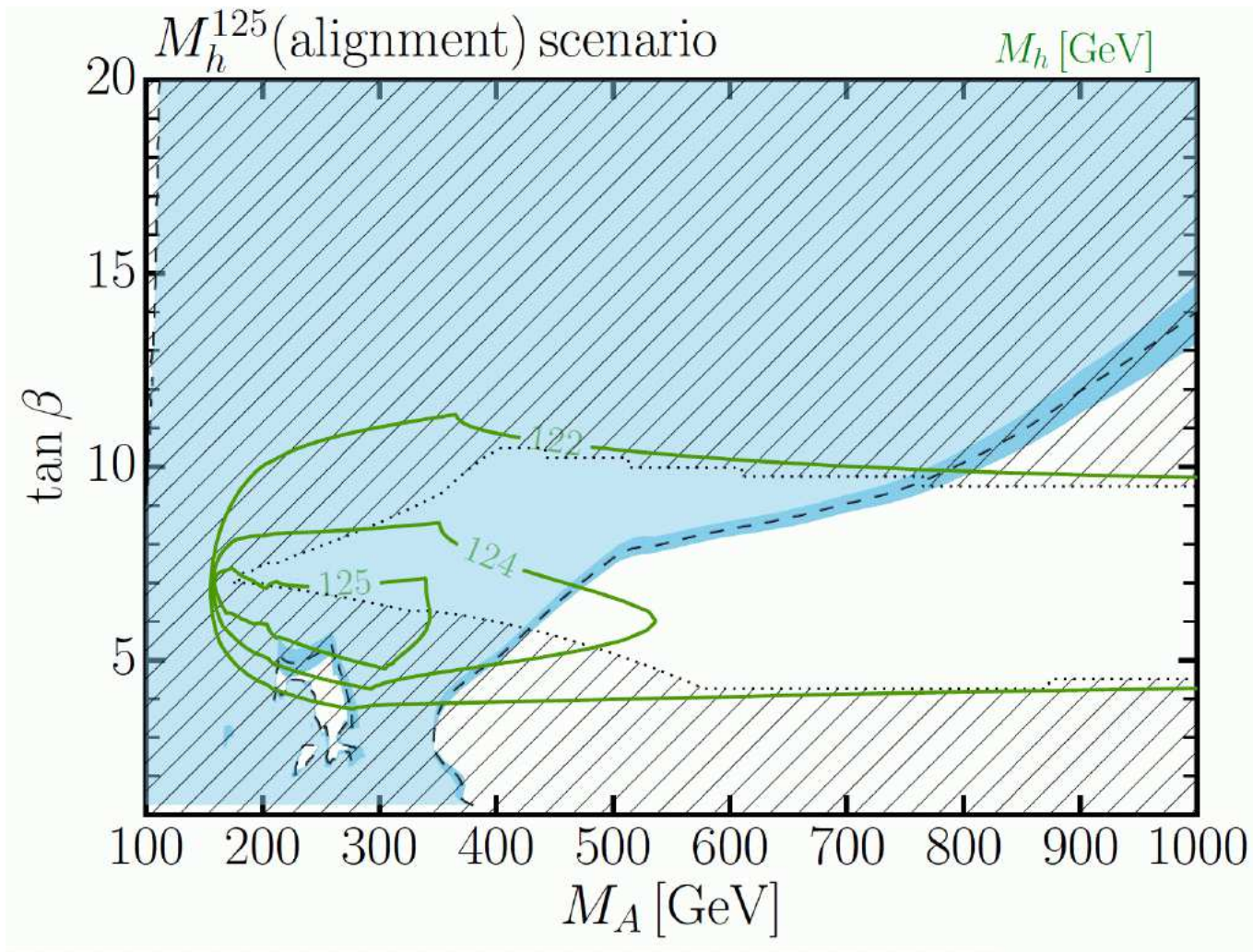
$$A_t = A_b = A_\tau$$

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 M_2 &= 180 \text{ GeV}, \quad M_3 = 2.5 \text{ TeV} \\
 X_t &= 2.5 \text{ TeV} \\
 A_t &= A_b = A_\tau
 \end{aligned}$$

⇒ Huge BR of heavy Higgses to EW-inos



$$M_{\tilde{Q}_3} = M_{\tilde{U}_3} = M_{\tilde{D}_3} = 2.5 \text{ TeV}$$

$$M_{\tilde{L}_3} = M_{\tilde{E}_3} = 2 \text{ TeV}$$

$$\mu = 7.5 \text{ TeV}, M_1 = 500 \text{ GeV}$$

$$M_2 = 1 \text{ TeV}, M_3 = 2.5 \text{ TeV}$$

$$A_t = A_b = A_\tau = 6.25 \text{ TeV}$$

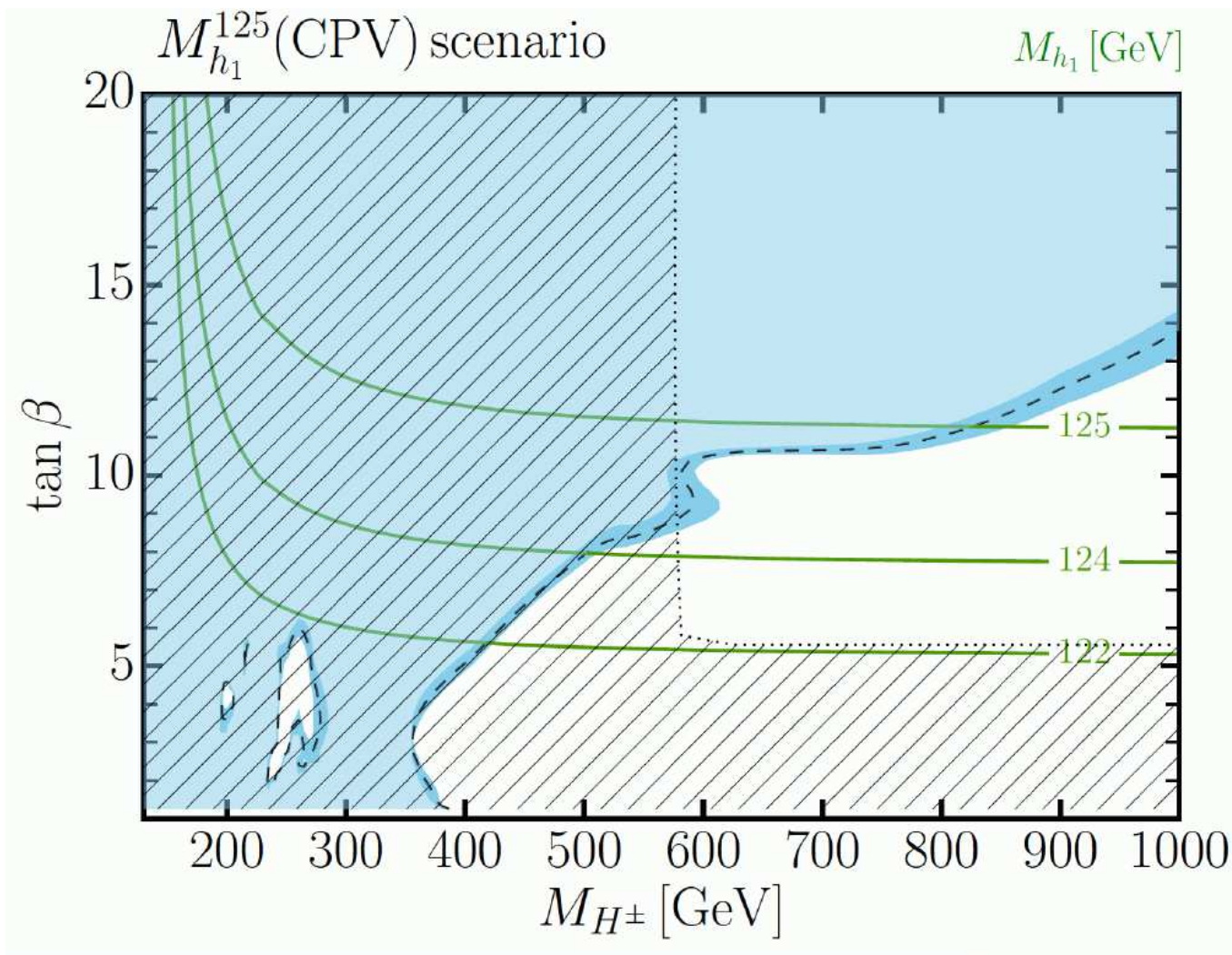
$\Rightarrow h$ SM-like for very low M_A

LHC Higgs searches for complex parameters:

$h_1 \sim H_{125}$, $M_{h_2} \approx M_{h_3}$, **CPV: large h_2 - h_3 mixing** possible:

Higgs bosons as intermediate states in $\{b\bar{b}, gg\} \rightarrow h_a \rightarrow \tau\tau$

$$\left| \begin{array}{c}
 \begin{array}{c} b \\ \tau^- \\ \hline \bullet \end{array} \text{---} h_1 \text{---} \begin{array}{c} \tau^- \\ \tau^+ \\ \hline \bullet \end{array} + \begin{array}{c} b \\ \tau^- \\ \hline \bullet \end{array} \text{---} h_2 \text{---} \begin{array}{c} \tau^- \\ \tau^+ \\ \hline \bullet \end{array} + \begin{array}{c} b \\ \tau^- \\ \hline \bullet \end{array} \text{---} h_3 \text{---} \begin{array}{c} \tau^- \\ \tau^+ \\ \hline \bullet \end{array} \\
 \hline
 \sum_{a=1}^3 \begin{array}{c} g \\ \tau^- \\ \hline \bullet \end{array} \text{---} h_a \text{---} \begin{array}{c} \tau^- \\ \tau^+ \\ \hline \bullet \end{array} + \begin{array}{c} g \\ \tau^- \\ \hline \bullet \end{array} \text{---} h_a \text{---} \begin{array}{c} \tau^- \\ \tau^+ \\ \hline \bullet \end{array} + \begin{array}{c} g \\ \tau^- \\ \hline \bullet \end{array} \text{---} h_a \text{---} \begin{array}{c} \tau^- \\ \tau^+ \\ \hline \bullet \end{array}
 \end{array} \right|^2$$



$$M_{\tilde{Q}_3} = M_{\tilde{U}_3} = M_{\tilde{D}_3} = 2 \text{ TeV}$$

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$$\mu = 1.65 \text{ TeV}, M_1 = 1 \text{ TeV}$$

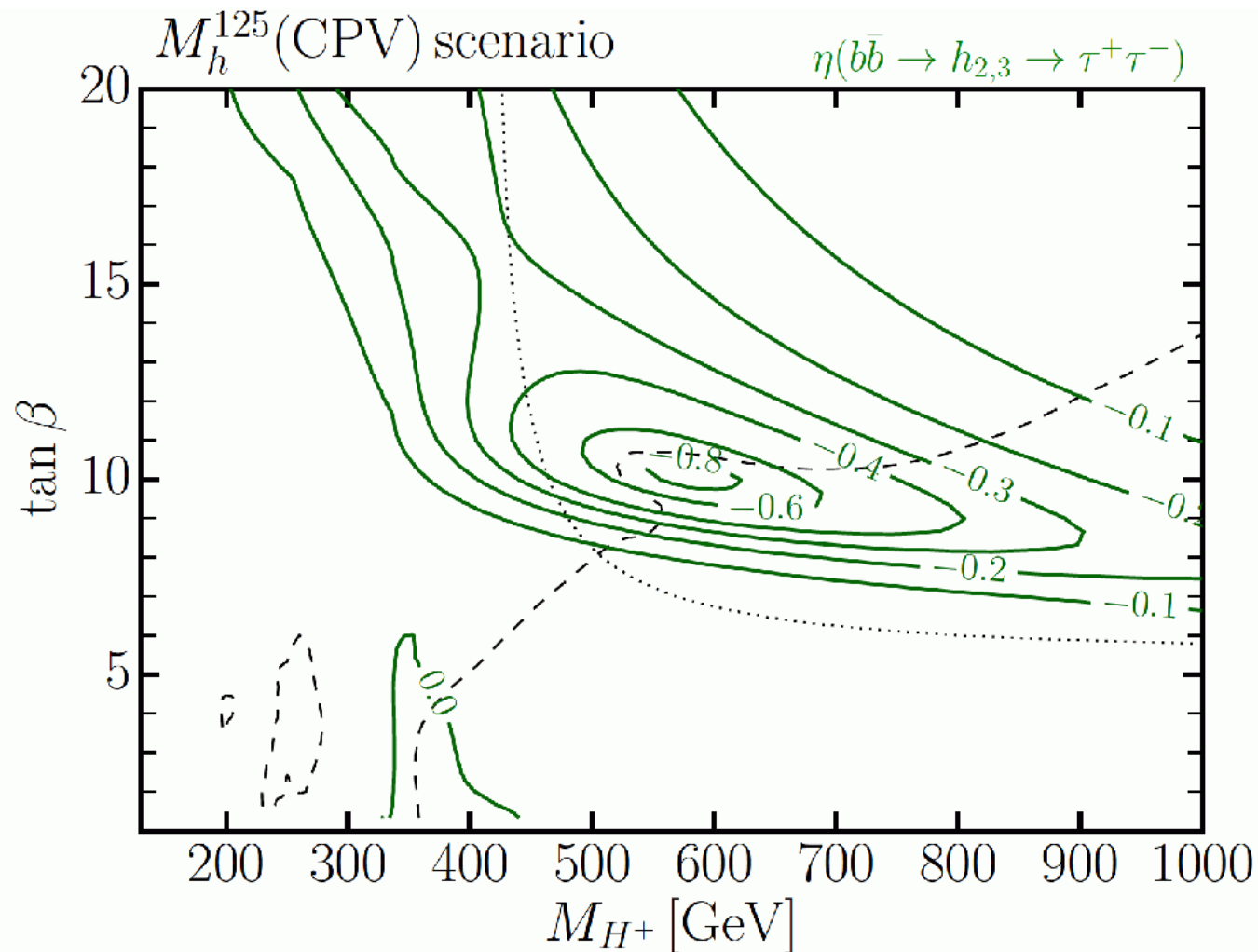
$$M_2 = 1 \text{ TeV}, M_3 = 2.5 \text{ TeV}$$

$$|A_t| = \mu / \tan \beta + 2.8 \text{ TeV}$$

$$\phi_{A_t} = 2/15 \pi$$

$$|A_t| = A_b = A_\tau$$

⇒ reduced coverage due to h_2 - h_3 interference



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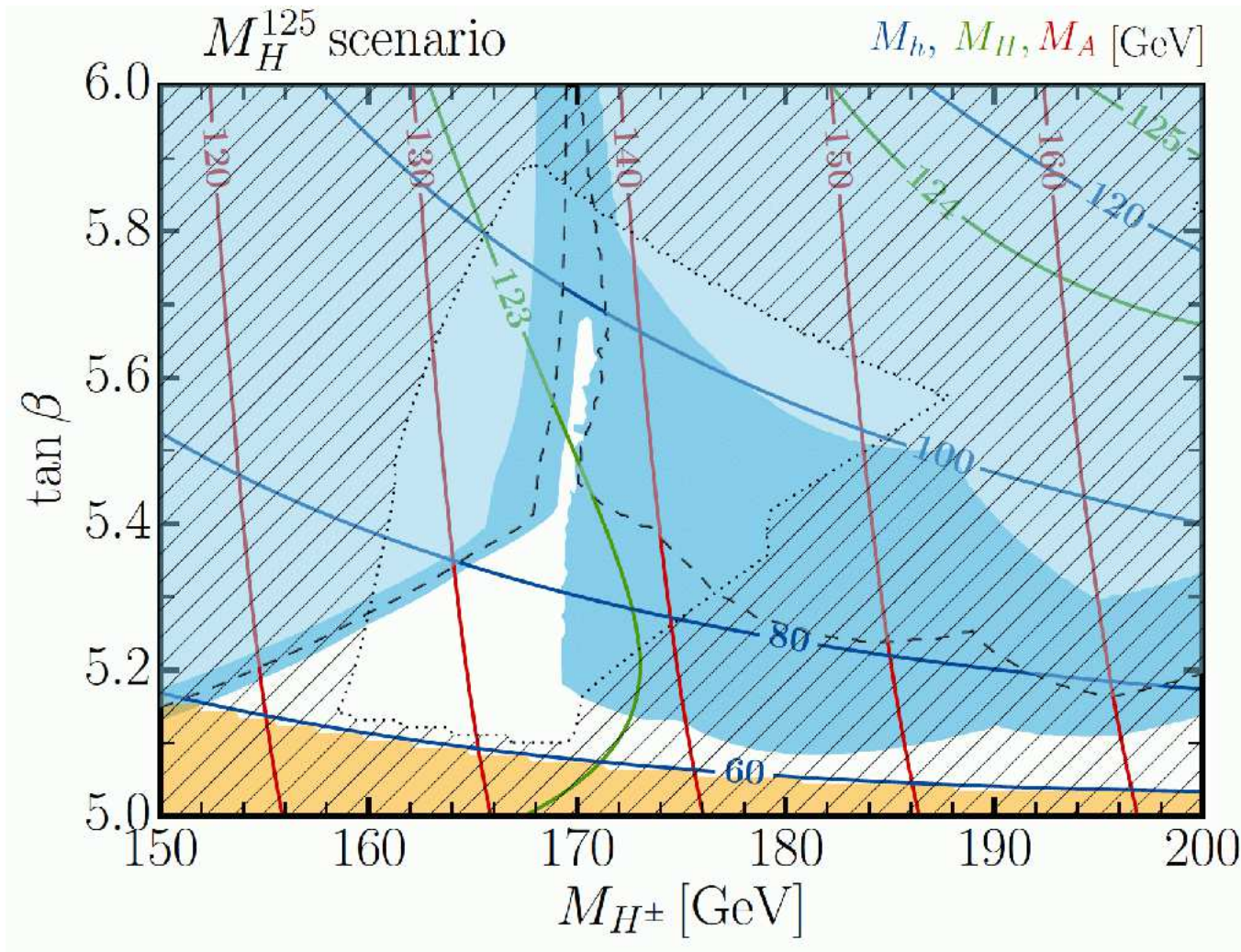
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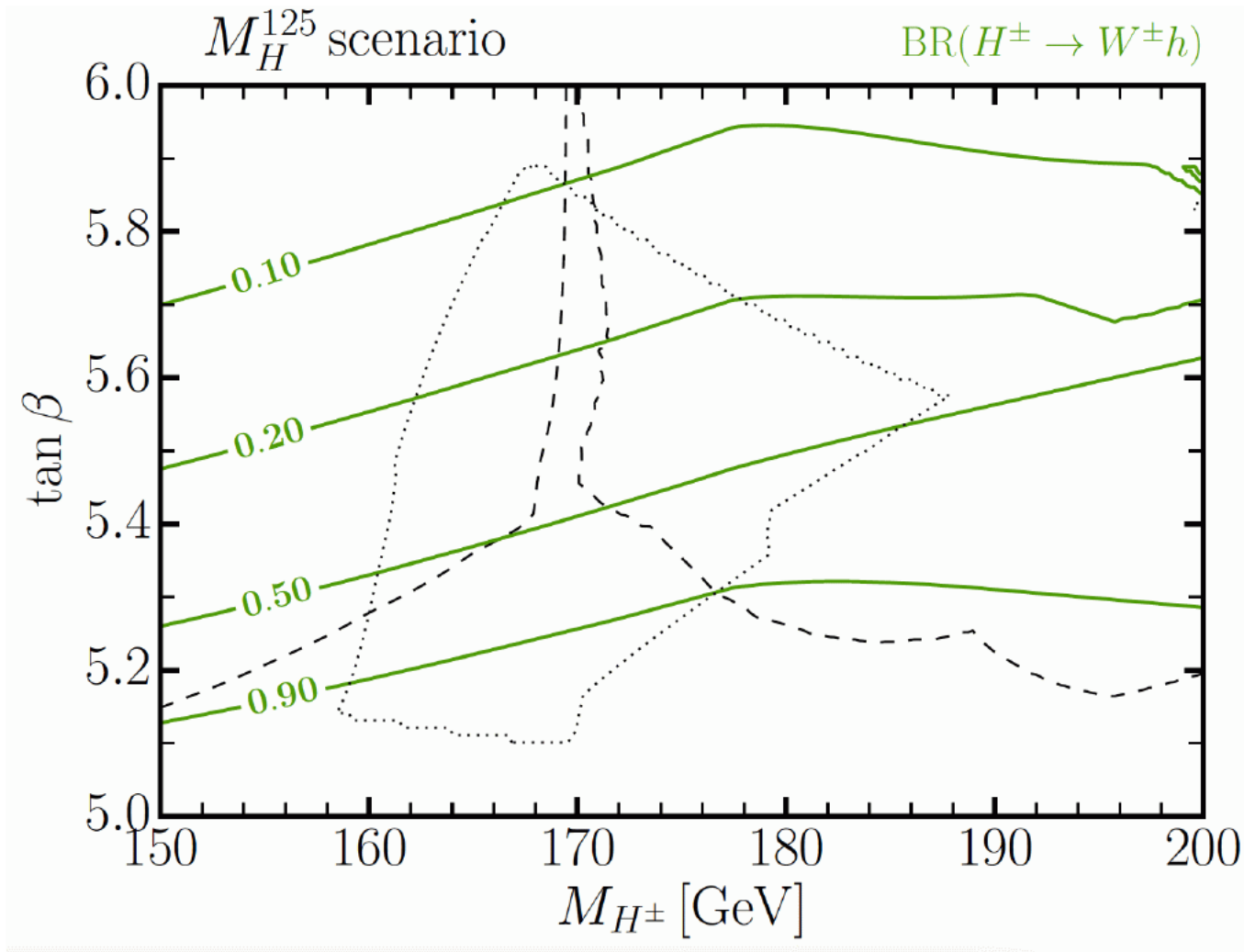
$$|A_t| = A_b = A_\tau$$

⇒ reduced coverage due to h_2 - h_3 interference



$$\begin{aligned}
 M_{\tilde{Q}_3} &= M_{\tilde{U}_3} = 750 \text{ GeV} \\
 &\quad - 2(M_{H^\pm} - 150 \text{ GeV}) \\
 M_{\tilde{L}_3} &= M_{\tilde{E}_3} = M_{\tilde{D}_3} = 2 \text{ TeV} \\
 \mu &= [5.8 \text{ TeV} \\
 &\quad + 20(M_{H^\pm} - 150 \text{ GeV})] \times \\
 &\quad M_{\tilde{Q}_3}/750 \text{ GeV} \\
 M_1 &= M_{\tilde{Q}_3} - 75 \text{ GeV} \\
 M_2 &= 1 \text{ TeV}, \quad M_3 = 2.5 \text{ TeV} \\
 A_t &= A_b = A_\tau = 0.65 M_{\tilde{Q}_3}
 \end{aligned}$$

⇒ exotic solution still viable!



$$\begin{aligned}
 M_{\tilde{Q}_3} &= M_{\tilde{U}_3} = 750 \text{ GeV} \\
 &\quad - 2(M_{H^\pm} - 150 \text{ GeV}) \\
 M_{\tilde{L}_3} &= M_{\tilde{E}_3} = M_{\tilde{D}_3} = 2 \text{ TeV} \\
 \mu &= [5.8 \text{ TeV} \\
 &\quad + 20(M_{H^\pm} - 150 \text{ GeV})] \times \\
 &\quad M_{\tilde{Q}_3}/750 \text{ GeV} \\
 M_1 &= M_{\tilde{Q}_3} - 75 \text{ GeV} \\
 M_2 &= 1 \text{ TeV}, \quad M_3 = 2.5 \text{ TeV} \\
 A_t &= A_b = A_\tau = 0.65 M_{\tilde{Q}_3}
 \end{aligned}$$

\Rightarrow large $\text{BR}(H^\pm \rightarrow W^\pm h)$

3. Implications for the HL-LHC and the ILC

[H. Bahl, P. Bechtle, S.H., S. Liebler, T. Stefaniak, G. Weiglein '19 – PRELIMINARY]

HL-LHC:

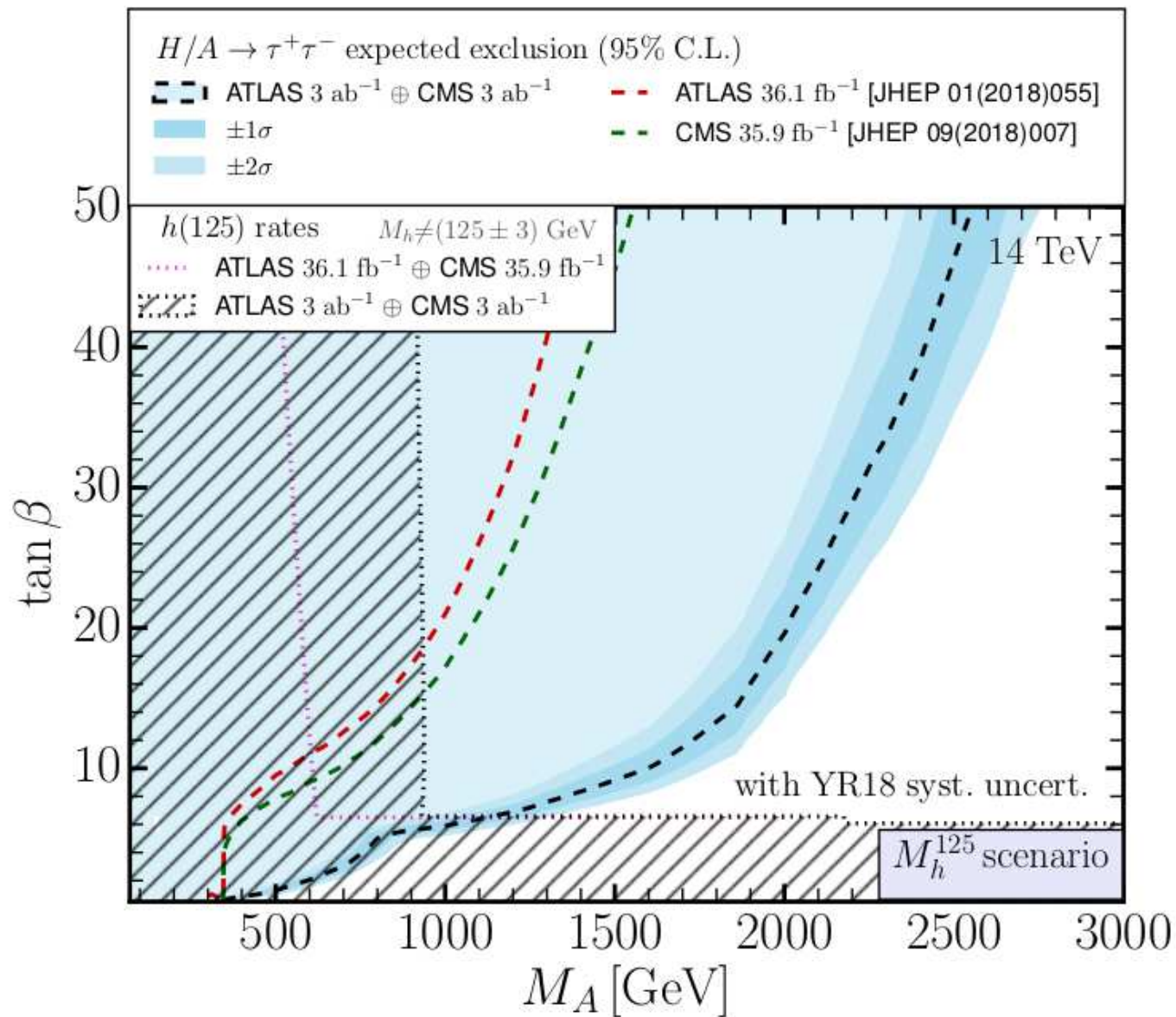
- will improve direct search limits
- will improve rate measurements (production \times decay)
systematic/theory uncertainties: S2 scenario

[M. Cepeda et al. '19 – YR18]

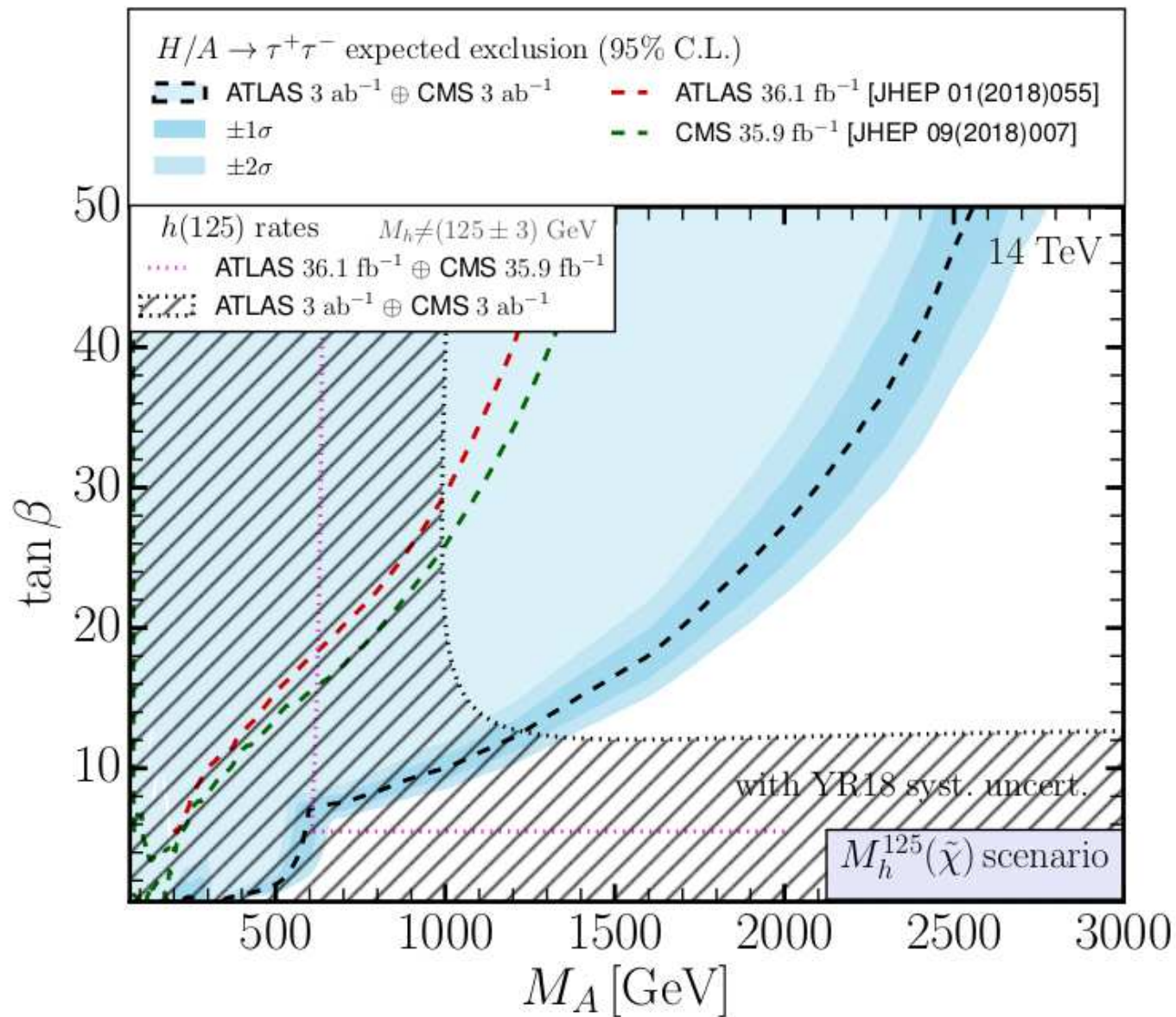
ILC:

- will improve rate measurements (no theory assumptions!)
 - 250 fb^{-1} at ILC250 \oplus 500 fb^{-1} at ILC500
 - polarization: $P(e^-, e^+) = (-80\%, +30\%)$

[T. Barklow, K. Fujii, S. Jung, R. Karl, J. List, T. Ogawa, M. Peskin, J. Tian '17]



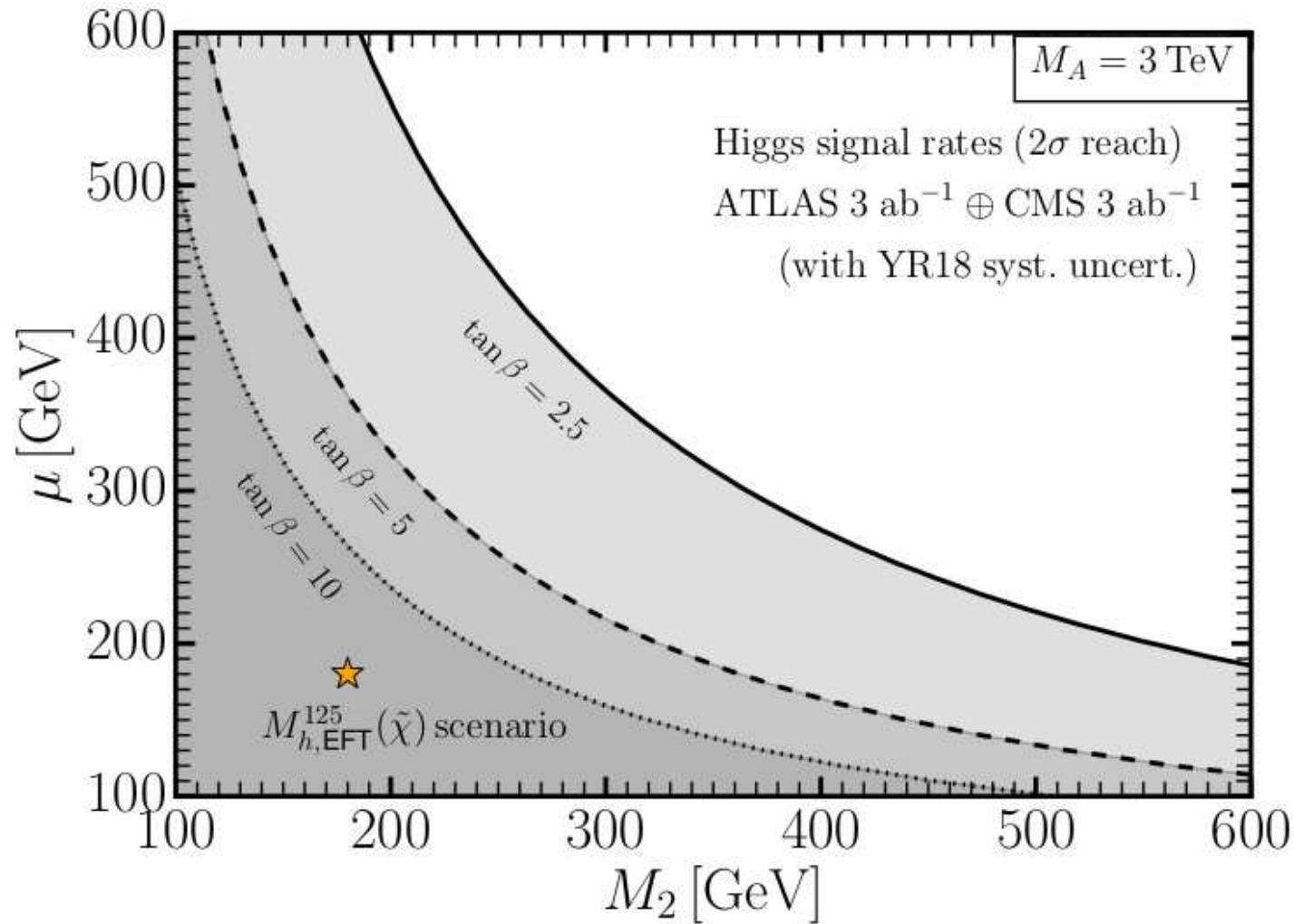
⇒ direct and indirect measurements: $M_A \gtrsim 1200$ GeV



\Rightarrow direct and indirect measurements: $M_A \gtrsim 1200$ GeV

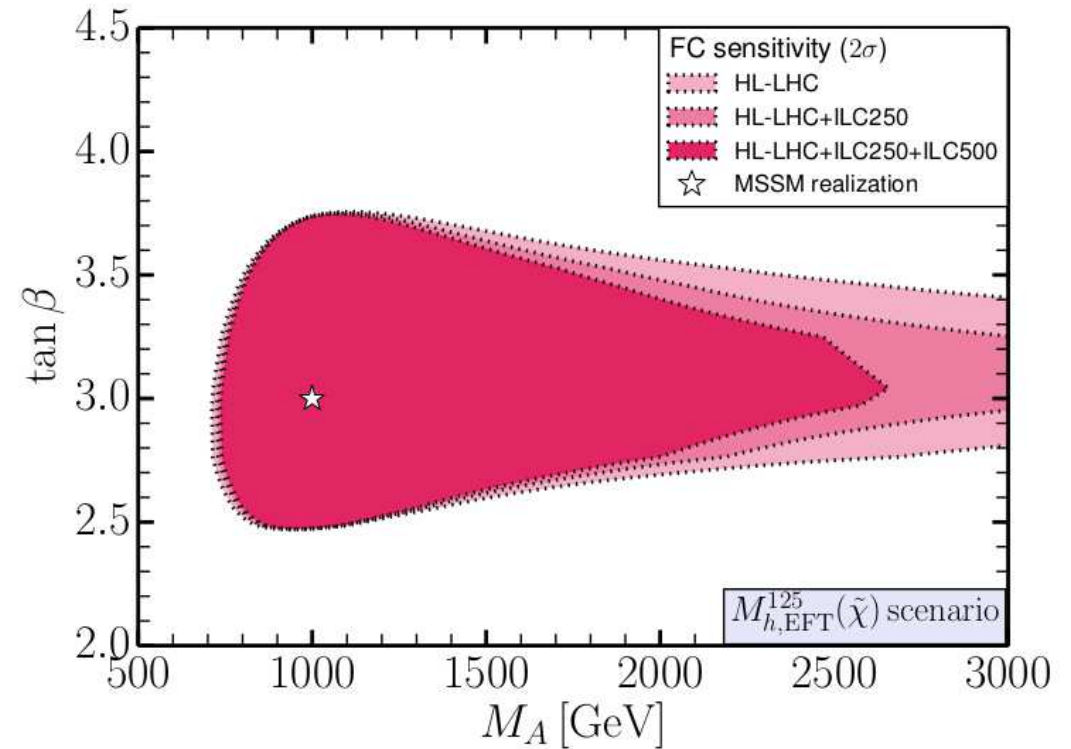
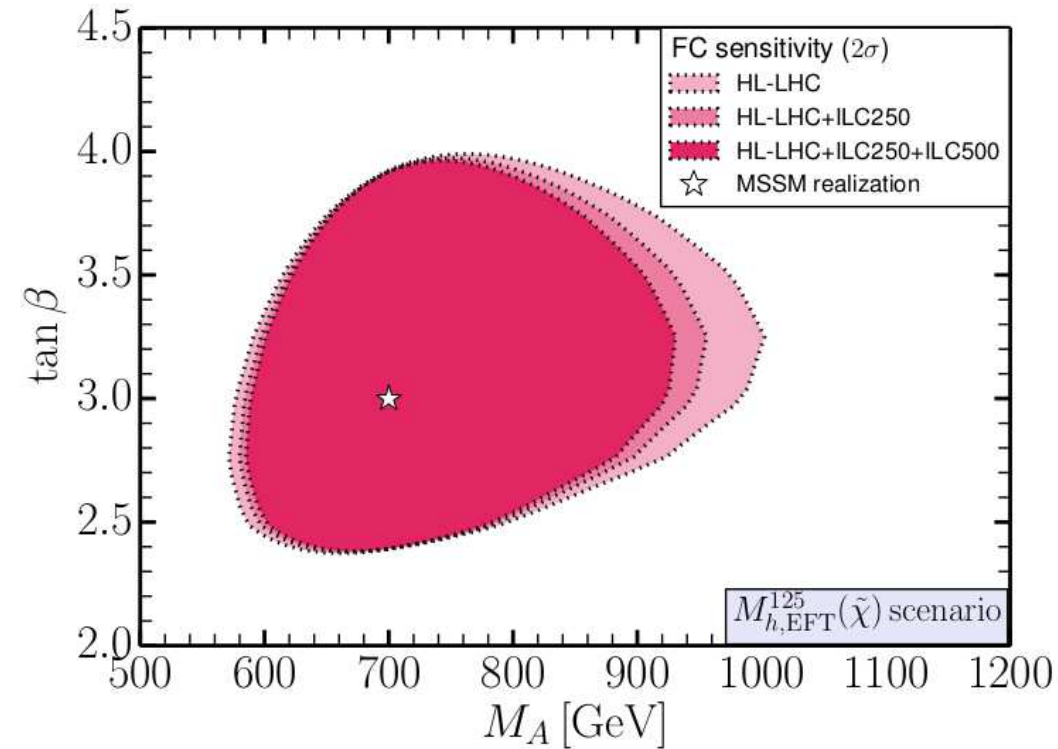
Indirect HL-LHC reach in $M_{h,\text{EFT}}^{125}(\tilde{\chi})$ scenario [H. Bahl et al., PRELIMINARY]

⇒ reach for charginos (mainly) via $h \rightarrow \gamma\gamma$:



⇒ strong reach for low $\tan \beta$

- Assume a realization of an MSSM point
- What limits can be set from rate/coupling measurements?



⇒ small improvements for $M_A = 700$ GeV

⇒ only ILC measurements give upper limit for $M_A = 1000$ GeV

4. Conclusios

- **SUSY** is (still) the best-motivated BSM scenario
 - unconstrained MSSM: 105 new parameters
 - constrained: CMSSM, NUHM, SU(5), mAMSB, sub-GUT, FUT, ...
 - benchmark models: parameter planes
- Benchmark scenarios/searches: Data taken into account: Higgs/SUSY
Data on purpose not taken into account: EW/Flavor/DM
- New benchmark proposal:
 - M_h^{125} scenario: 2HDM-like model
 - $M_h^{125}(\tilde{\tau})$ scenario: light staus: $h \rightarrow \gamma\gamma$, $H/A \rightarrow \tilde{\tau}\tilde{\tau}$
 - $M_h^{125}(\tilde{\chi})$ scenario: light EW-inos: $H/A \rightarrow \tilde{\chi}_i^0 \tilde{\chi}_j^0, \tilde{\chi}_k^\pm \tilde{\chi}_l^\mp$
 - M_h^{125} (alignment) scenario: h SM-like for very low M_A
 - M_H^{125} scenario: $M_H \sim 125$ GeV, all Higgses light
 - $M_{h_1}^{125}$ (CPV) scenario: complex phases, h_2 - h_3 interference
- Implications for HL-LHC and ILC:
 - direct \oplus indirect HL-LHC reach: $M_A \gtrsim 1200$ GeV
 - interesting reach for charginos via $h \rightarrow \gamma\gamma$
 - ILC measurements can be crucial to set upper limits on M_A

Higgs Days at Santander 2019

Theory meets Experiment

16.-20. September




Contact: Sven.Heinemeyer@cern.ch

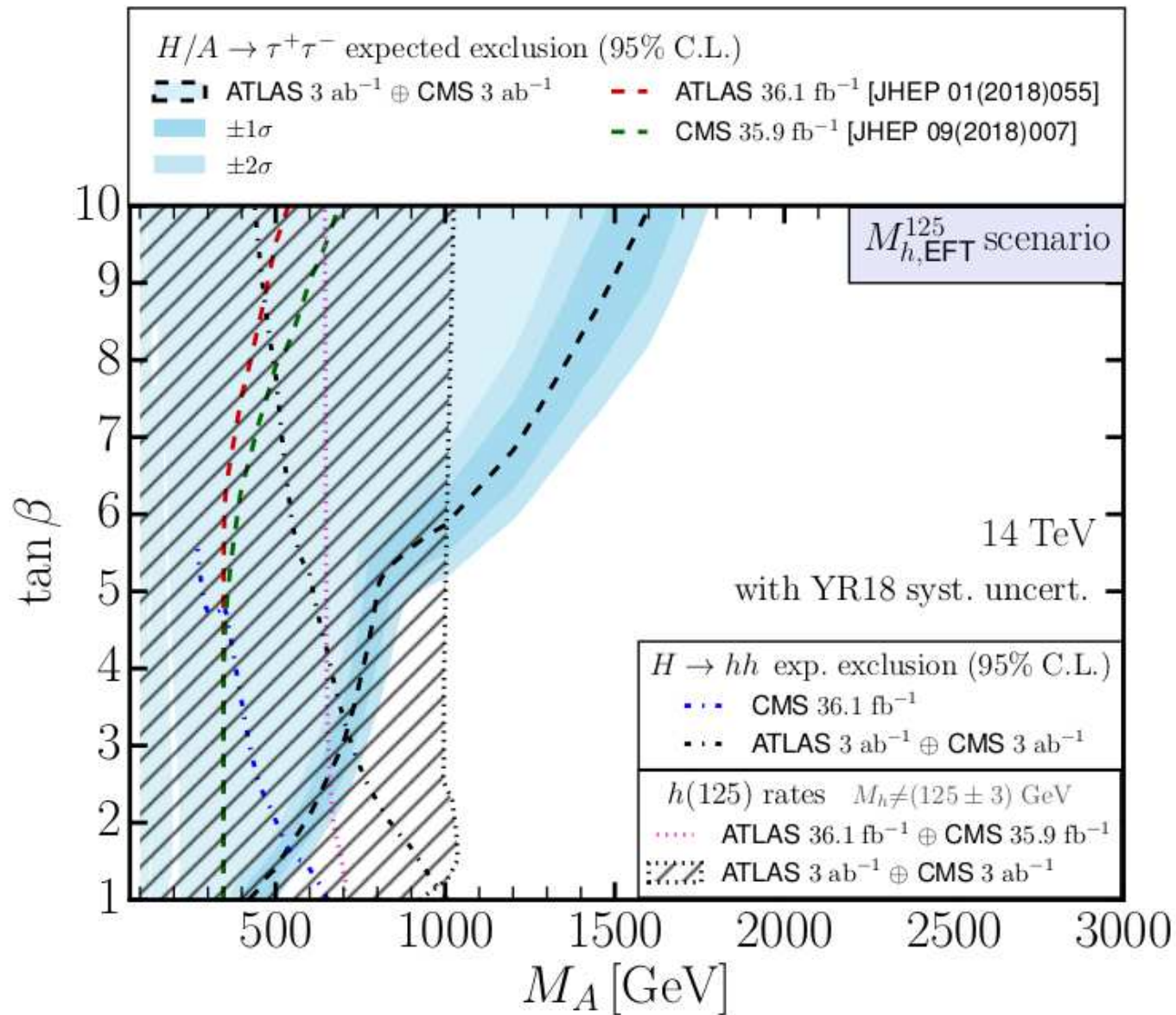
Local: Alicia.Calderon@cern.ch

Gervasio.Gomez@cern.ch

<http://hdays.csic.es>



Further Questions?



\Rightarrow indirect measurements stronger at low $\tan \beta$: $M_A \gtrsim 1000$ GeV